Development of Tailored Fiber Placement, Multi-Functional, High-Performance Composite Material Systems for High Volume Manufacture of Structural Battery Enclosure

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General Motors
2022 Annual Merit Review
June 21, 2022

Project ID: MAT198

Overview

Timeline

- Project Start Date: April 1, 2021#
- Project End Date: June 30, 2024
- Percent Complete: 35%

Budget

- Total project funding
  - Total : $10,330,000
  - DOE Share: $7,500,000
  - Contractor Share: $2,830,000
- Funding for FY21:
  - Total: $436,369
  - DOE share: $316,804
  - Contractor share: $119,565

#requested DOE a new timeline for the project due to late start

Barriers and Technical Targets

Barriers addressed*

A. ***Material systems development :*** Structural composite material system having multi-functional capabilities such as hybrid fibers (ex. carbon and glass), self-health monitoring, fire-retardance, and electro-magnetic compatibility (EMC) to make a positive business case (cost increase per pound saved is less than $5)

B. ***Predictive technology development:*** Modeling tools to predict the performance of manufacturing process and structural design within 15% of experimental results. AI/ML technology development for process monitoring to save costs of inspection and scrap during manufacturing.

C. ***Demonstration:*** Using the developed material systems, design, build, and test a structural composite battery enclosure, and compare the weight and performance metrics with that of a baseline metallic assembly.

*2017 U.S. DRIVE Roadmap Report, section 4

Participants

General Motors
Coats
Columbia University
Continental Structural Plastics (CSP)
ESI Group, NA
Michigan State University
University of Southern California

Relevance

Battery enclosures

- Battery enclosures are the relatively new structural assemblies in the automotive industry.
- Suppliers are exploring and working closely with OEMs to propose various designs and making adjustment to their investment plans.
- Materials are key and are investigated industry-wide to produce structurally durable assembly at a minimum cost.

High Performance Multi-functional Composite Material Systems

- Hybrid carbon and glass fibers in various architectures for cost-effective business case ($\geq$ 25 Msi, strain $\geq$ 1%)
- Self-health monitoring electronic circuits embedded in the composite for value proposition
- Integrated fire-retardant material systems for use in the future design of components for the battery enclosures
- High-pressure resin transfer molding (HP-RTM) for volume manufacturing needed for automotive industry
- Predictive computational tools for virtual design and eliminating cost of trial-and-error iterations
- AI/ML technologies for process monitoring and component design
- Reduce the lead time and costs to accelerate the implementation of structural automotive composites.
- Enable the usage of composites for significant light-weighting of automobiles and thus improve fuel economy/range, and lower emissions (reduce greenhouse gas emissions).

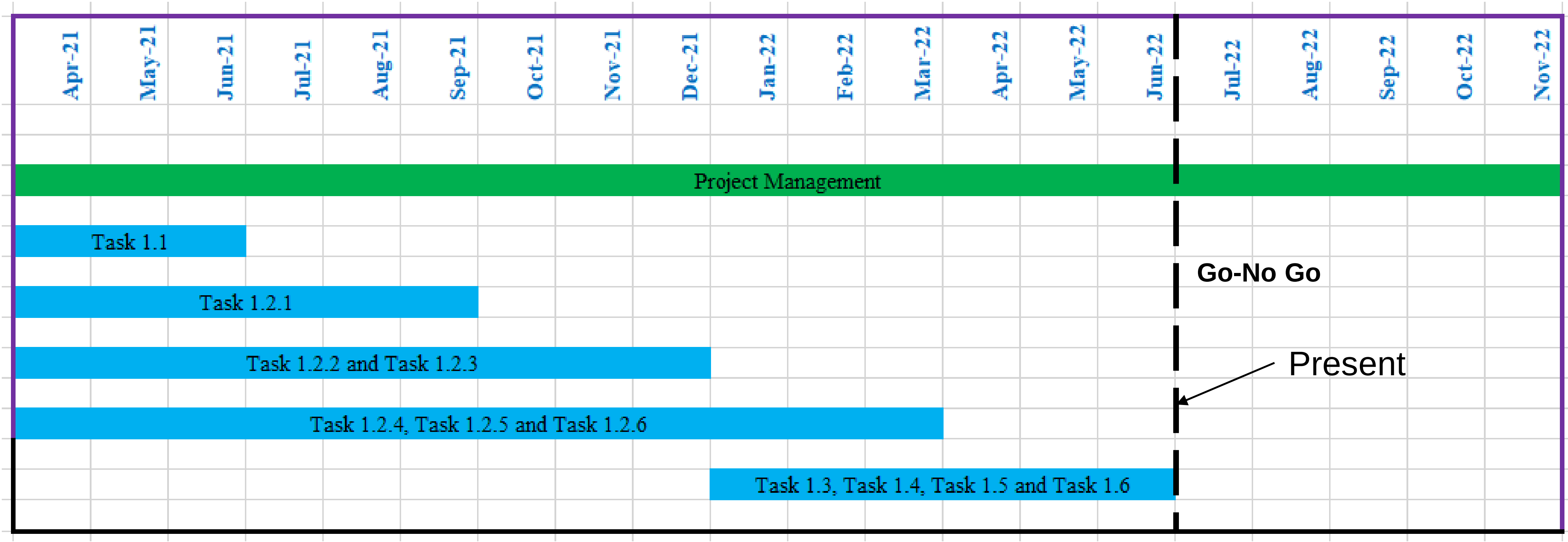
Cost Barrier

- Will demonstrate the ability to manufacture the automotive composite assembly at no more than **$5 per pound saved (2010 dollars)**.

Performance Barrier

- Will demonstrate the viability of composite materials to meet vehicle performance requirements while reducing vehicle assembly weight **by 25%** compared to a current steel structural battery enclosure. The cycle time to manufacture the composite panels need to be less than 3 minutes.

Milestones



Task	Details
Task 1.1	Determine functional requirements of baseline assembly
Task 1.2.1	Evaluate and develop an optimized fiber material systems
Task 1.2.2	Evaluate and develop required manufacturing model
Task 1.2.3	Evaluate and develop required structural model
Task 1.2.4	Evaluate and develop required self-health monitoring technologies
Task 1.2.5	Evaluate and develop AI/ML technologies for monitoring the manufacturing process
Task 1.2.6	Evaluate and develop cost models

Task	Details
Task 1.3	Initial structural design of battery enclosure
Task 1.4	Initial manufacturing design of battery enclosure
Task 1.5	Initial self-health monitoring technology implementation
Task 1.6	Initial AI/ML technology implementation

Go- No Go - Model error less than 15%

Approach/Strategy

- Hybrid fiber material system to lower the material costs – utilize the ductility improvement cited in the recent literature
- Optimum hybrid fiber ratio (carbon and glass) to maximize the performance for a given cost
- Engineer the microstructure (spacing of fiber bundles, stitch density) of the fiber preform to optimize the performance such as draping, injection (enhanced permeability)
- Multi-functional material systems including fire-retardance and EMC performance
- Develop the technology for high-pressure resin transfer molding (HP-RTM) process
- Develop the technology for self-health monitoring
- Develop the AI/ML technology for process monitoring
- Predictive modeling tools for the developed material systems for both manufacturing and structural performance
- Demonstrate the technology development by design, building, testing and comparing the performance metrics (weight, cost, performance) with that of a baseline metallic assembly.

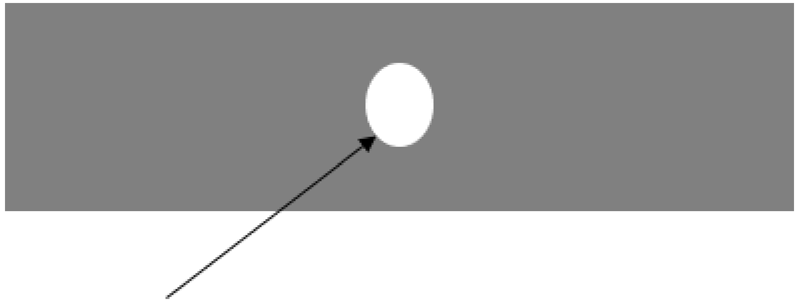
Technical Accomplishments and Progress

FY 22 Accomplishments

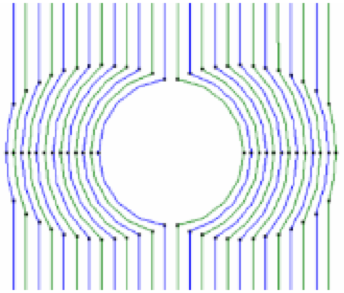
- Manufactured hybrid preforms with three comingling types, fabricated samples, and conducted tension and flex experiments
- Completed the study of hybrid material systems and ranked them for the metric of performance/cost and performance/mass
- Completed self-health monitoring (SHM) sensor design, damage location, and demonstration
- Completed temperature/humidity sensor design, sensor selection and experimentation
- Developed and validated a predictive model for high pressure resin transfer molding process
- Developed and validated a predicting model for structural performance of hybrid materials
- Developed an AI/ML model and validation is in progress

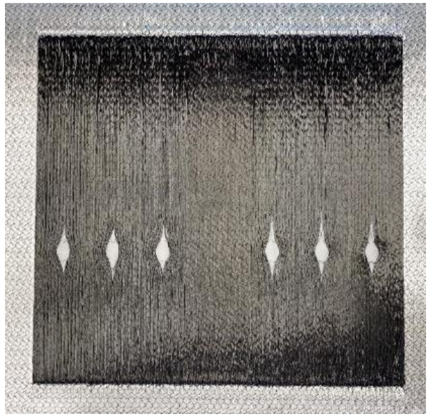
Demonstrations

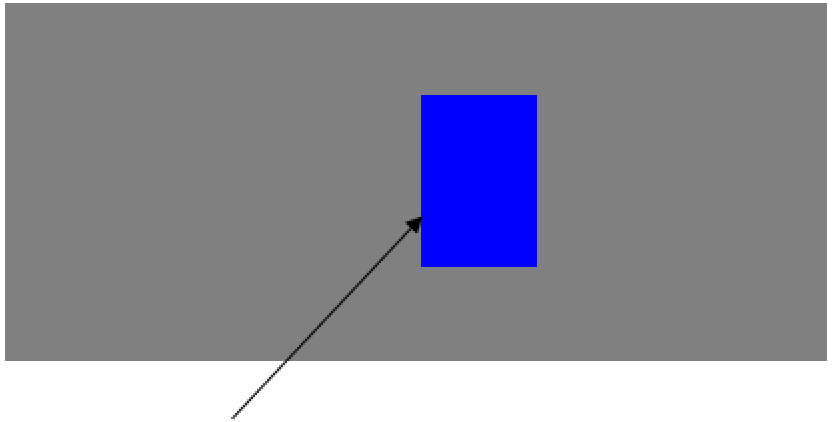
- Tailor fiber placement (TFP) designs with curvilinear fiber paths for efficiency
- Improving the draping by modifying the fiber spacing and stitch density
- Strategic manipulating permeability with stitch density



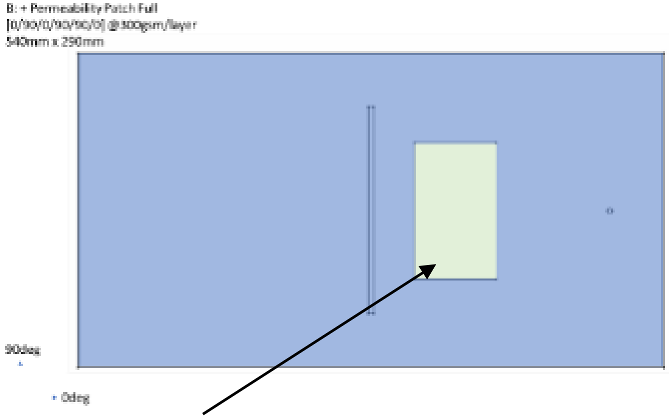
Hole



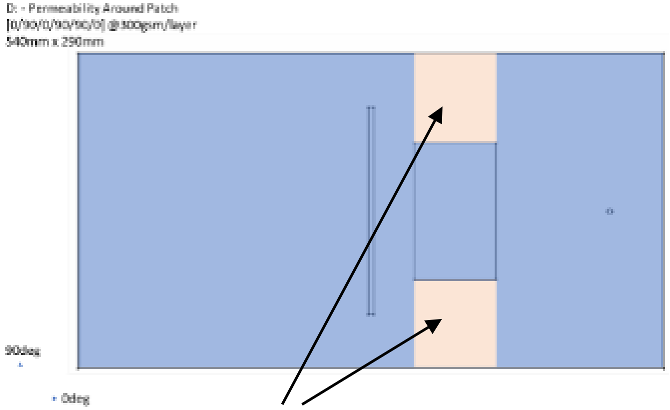




Strengthening patch

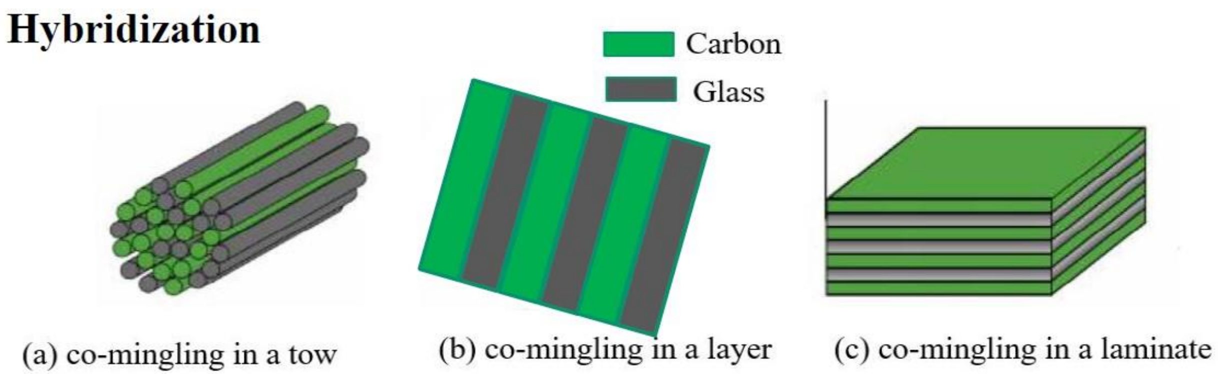


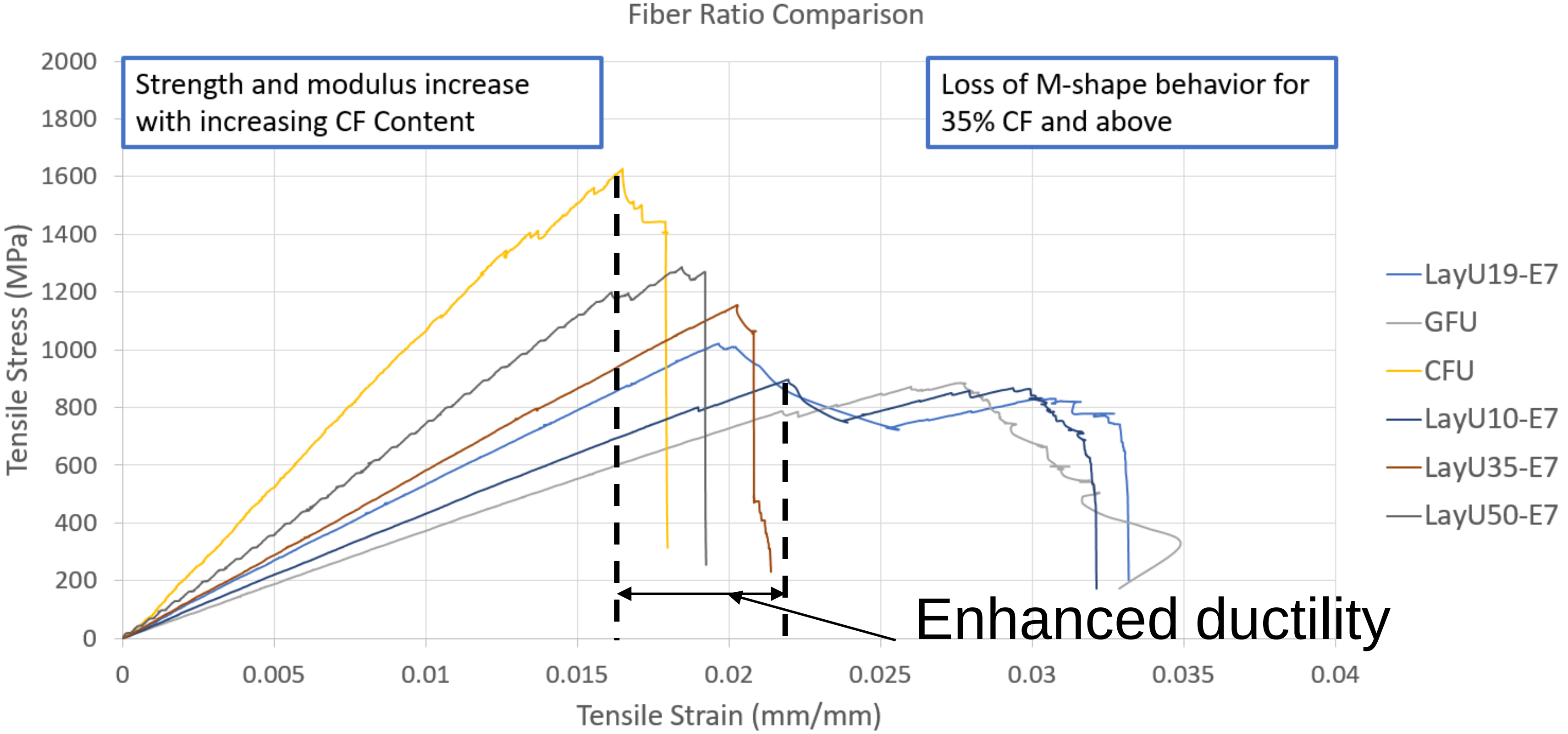
Highly permeable area
with high stitch density



Lower permeable area
with minimum stitch

Task 1.2.1 – Hybrid Material Systems

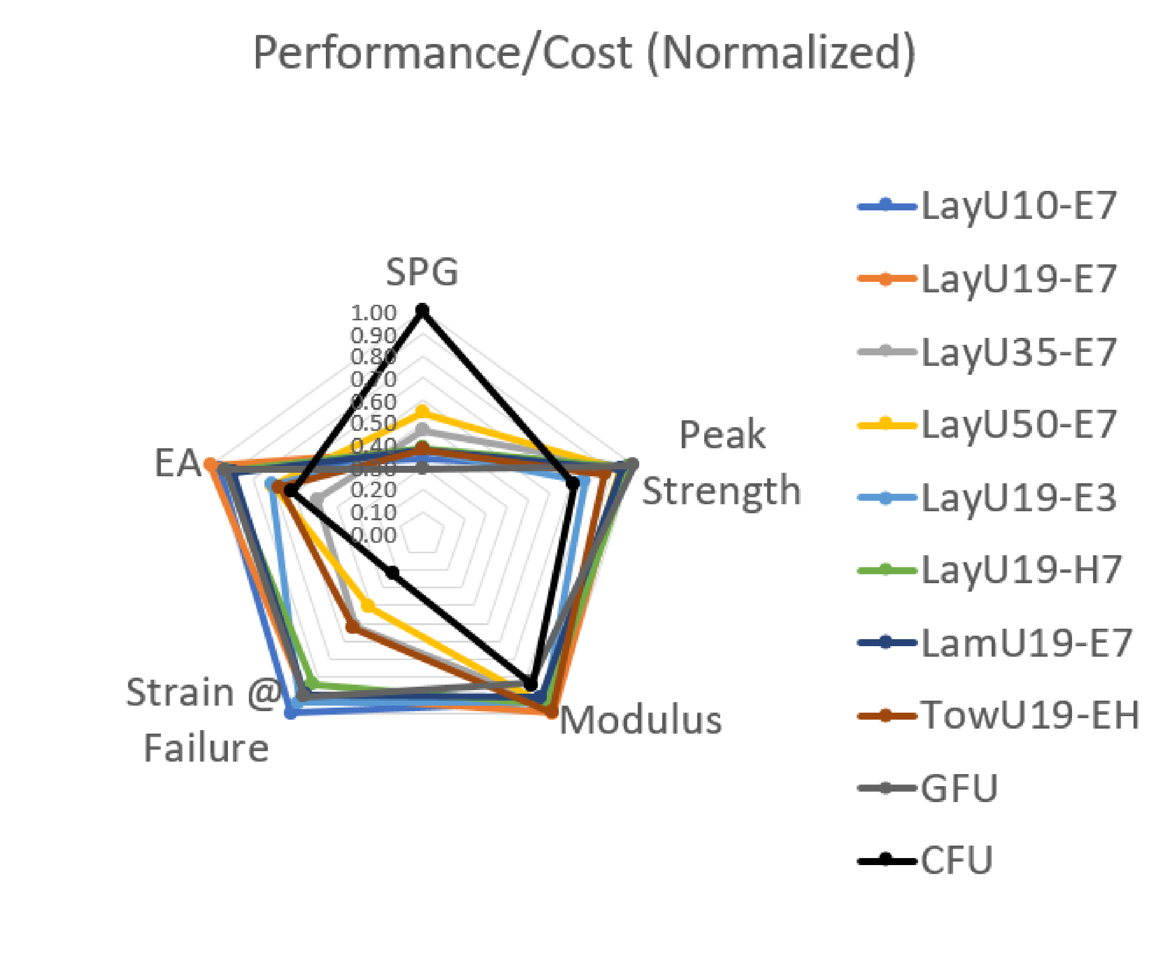


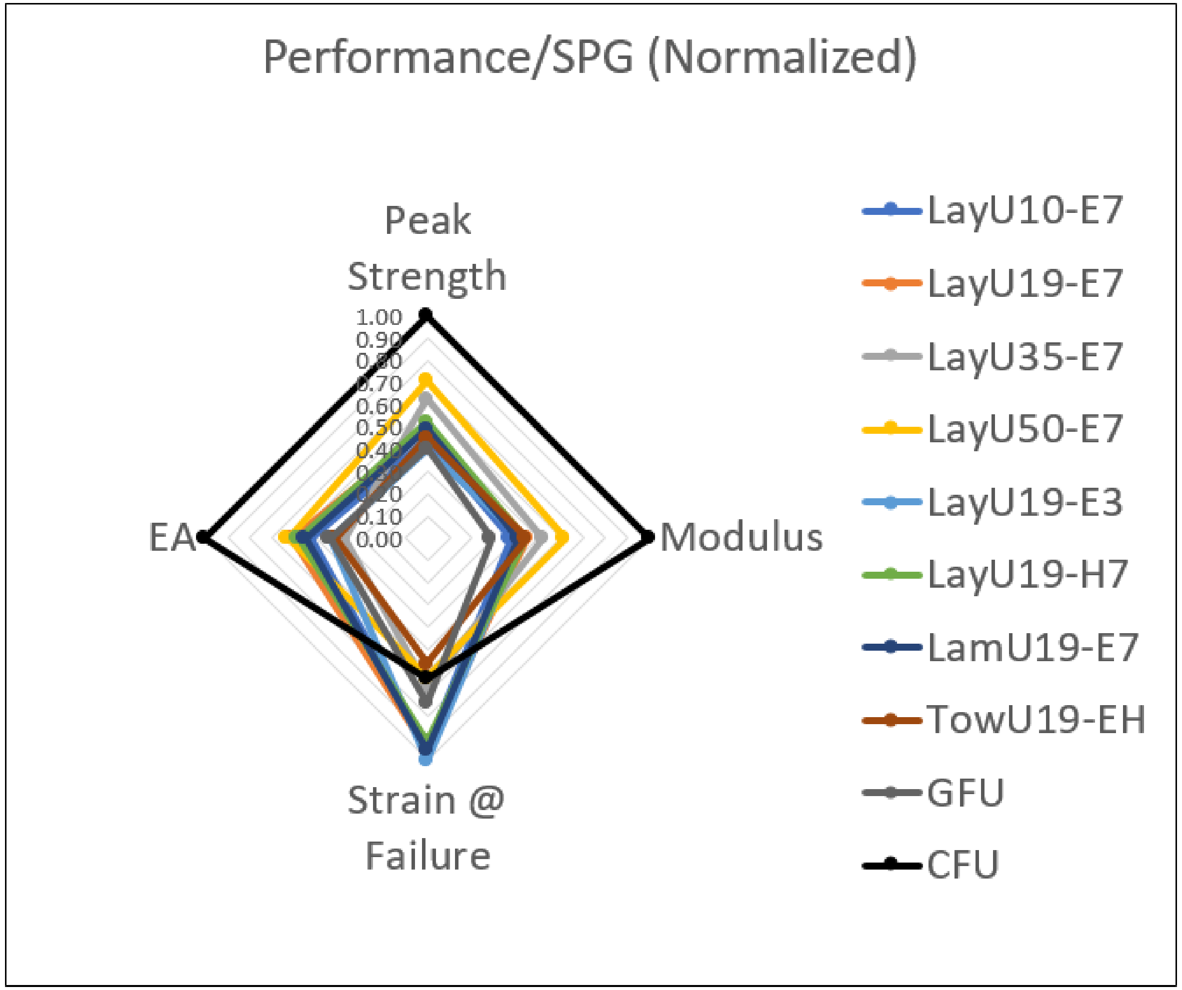


- Combining multiple reinforcement types in strategic ways can lead to enhanced ductility
- Different types of behavior depending on:
  - Content ratio of fiber types
  - Relative strength ratio (E- or S-glass vs. CF)

Molded plaque DOE to characterize properties
  - Carbon-to-glass ratios
  - Fiber types
  - Commingling type

Task 1.2.1 – Hybrid Material Systems – Performance Metrics

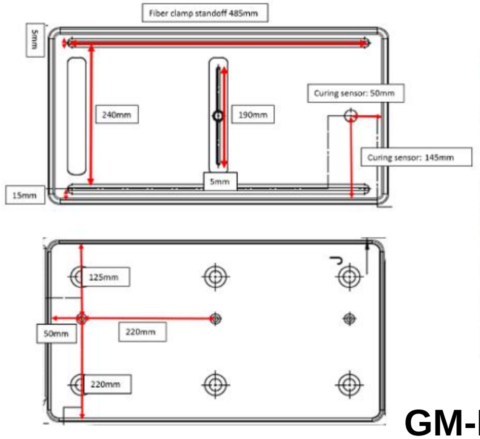




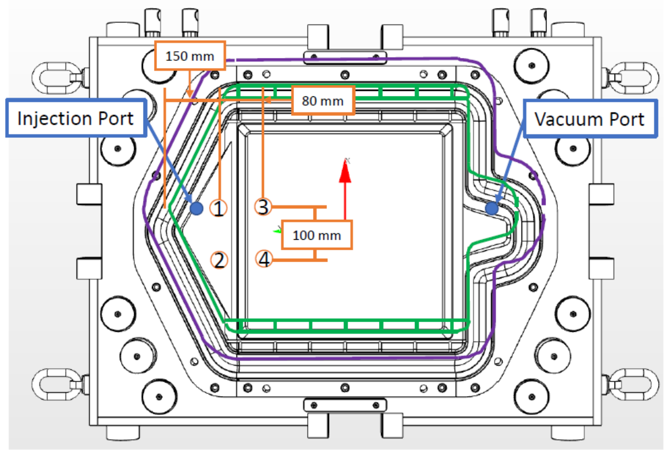
LayU19-E7 is best-performing hybrid

Task 1.2.2 – Evaluate and develop required manufacturing model

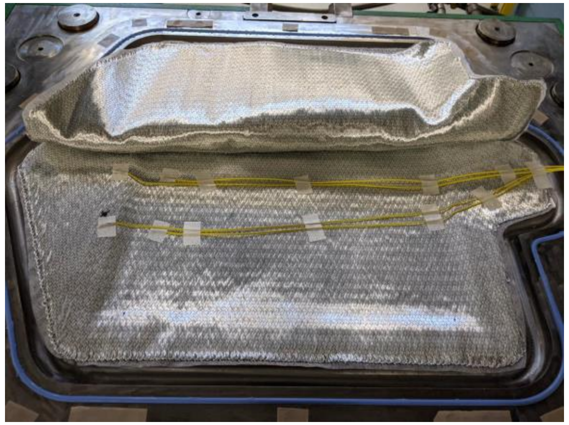
- Data collection for model development (temperature and pressure in a HP-RTM experiment)
- Manufacturing model development
- AI/ML process development



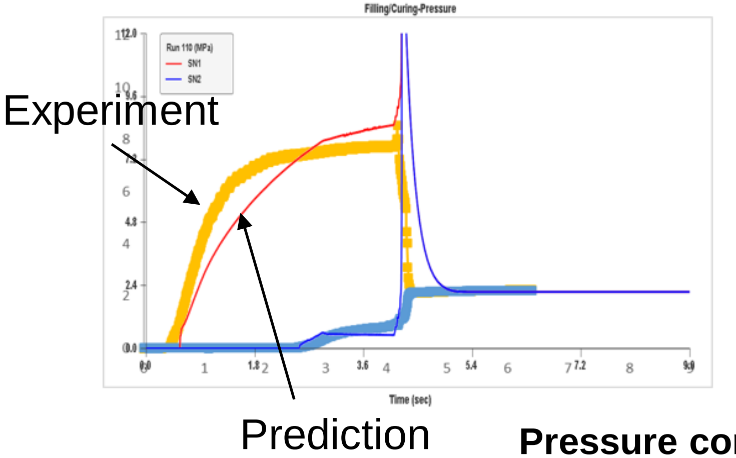
GM-Plaque tool for HP-RTM experiments

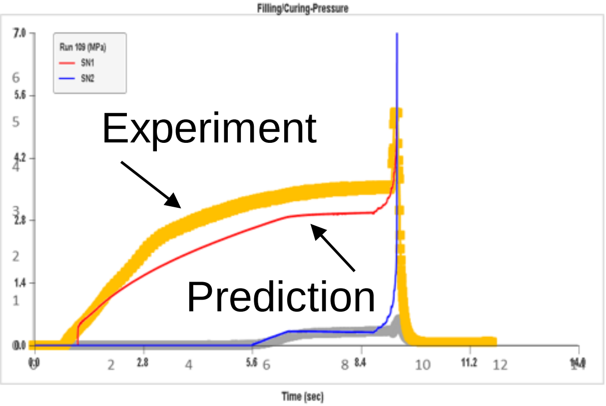


Teijin plaque tool

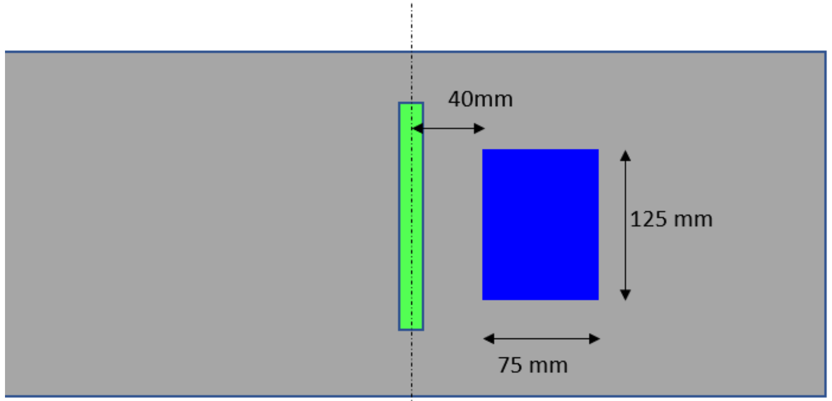


Thermocouple placement



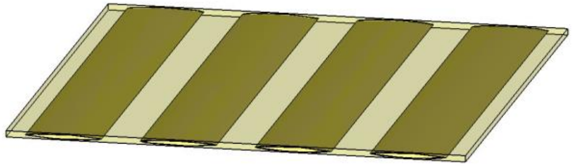


Pressure correlations

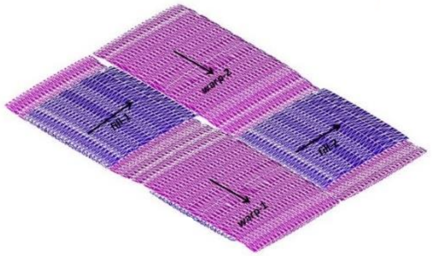


AI/ML process development

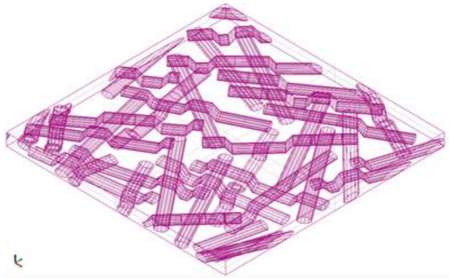
Task 1.2.3 – Evaluate and develop required structural model



Non-crimp fabric composites



Woven fabric composites

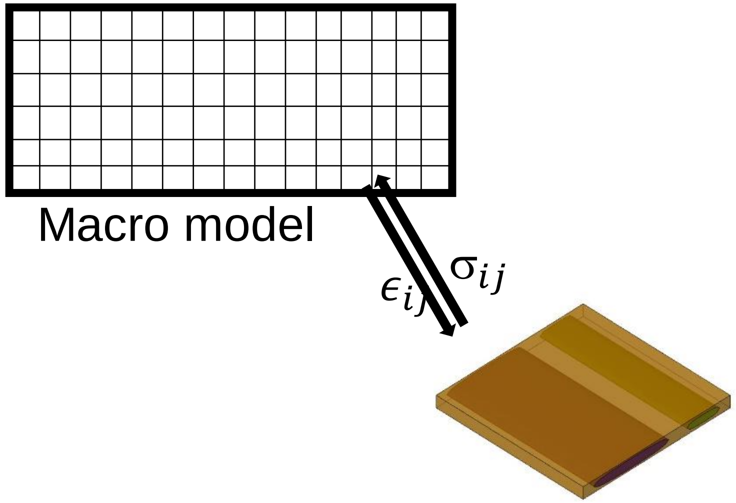


Chopped fiber composites

Outcome:

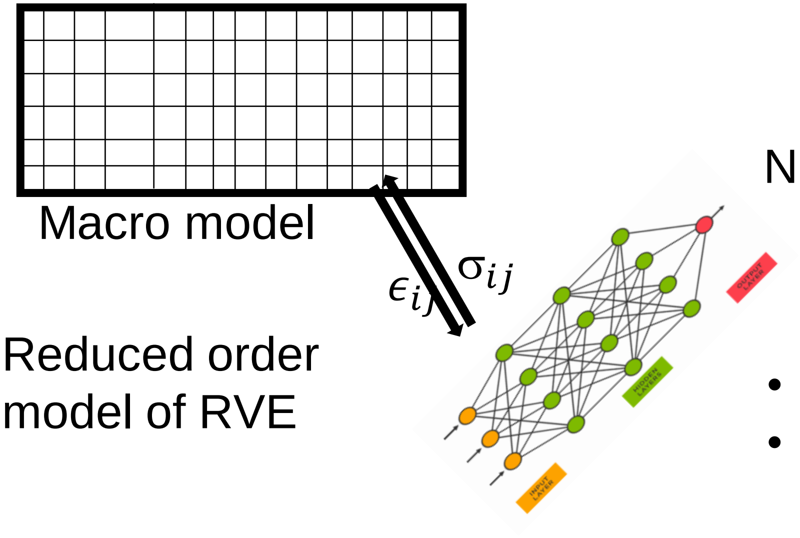
- Heterogeneous behavior, multiple failure mechanisms, manufacturing effects influencing the structural performance

Multi-scale Model Development



Reduced order model of RVE

Previous GM development (DE-EE0006826)

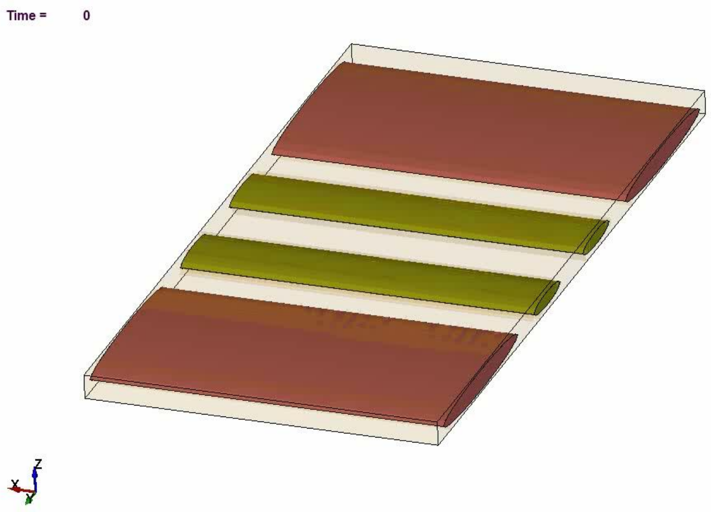


Neural Network

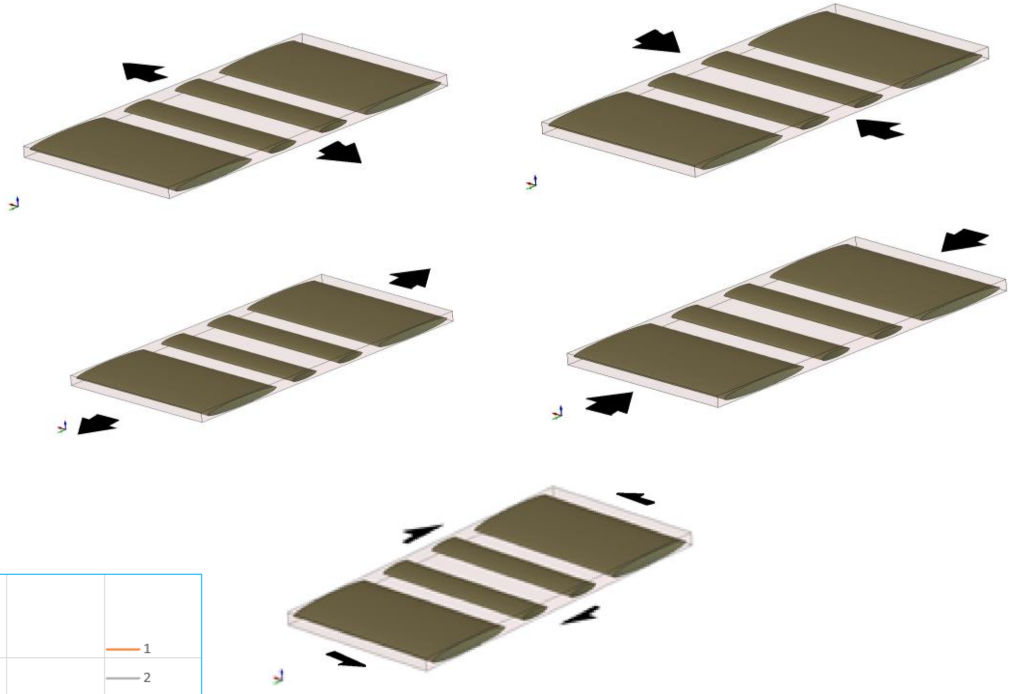
- Computationally efficient
- Enable Artificial Intelligence/Machine Learning models

New GM development (DE-EE0009204)

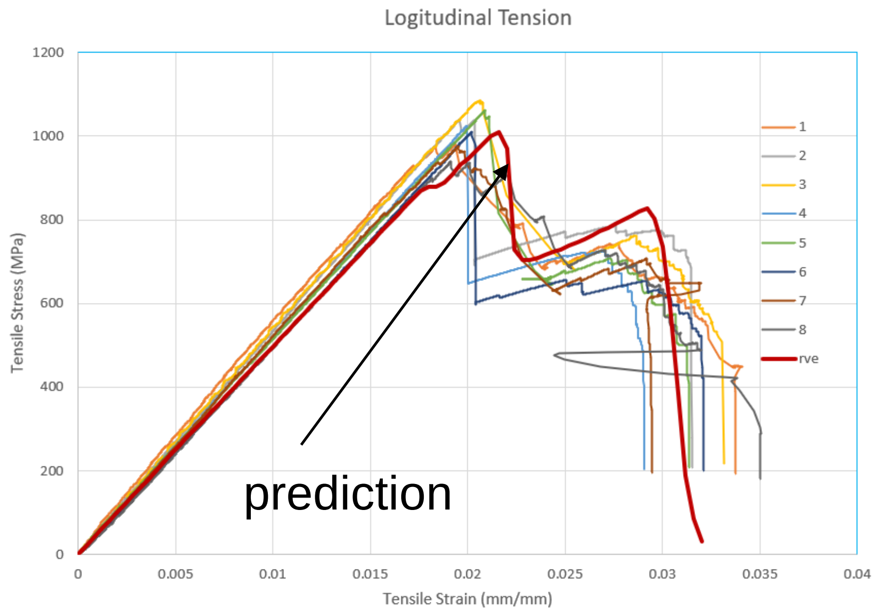
Task 1.2.3 – Evaluate and develop required structural model



RVE – Hybrid Composite



Multi-axial Loading

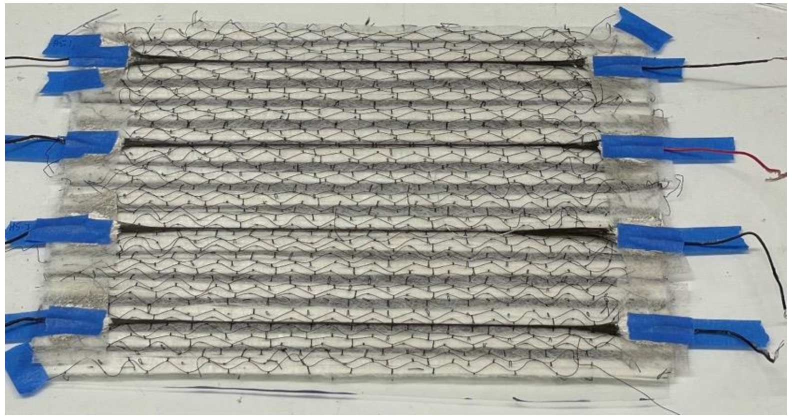


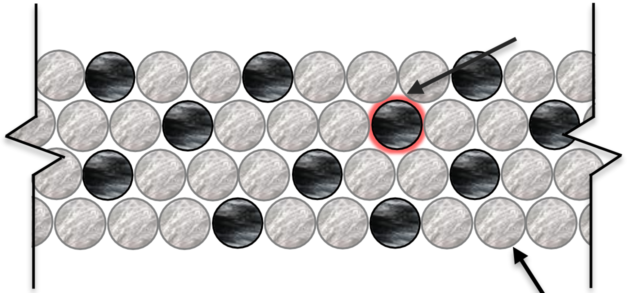
Simulation results are with in 3% of experimental results

Task 1.2.4 –Evaluate and develop required self-health monitoring technologies

Sensor Design*

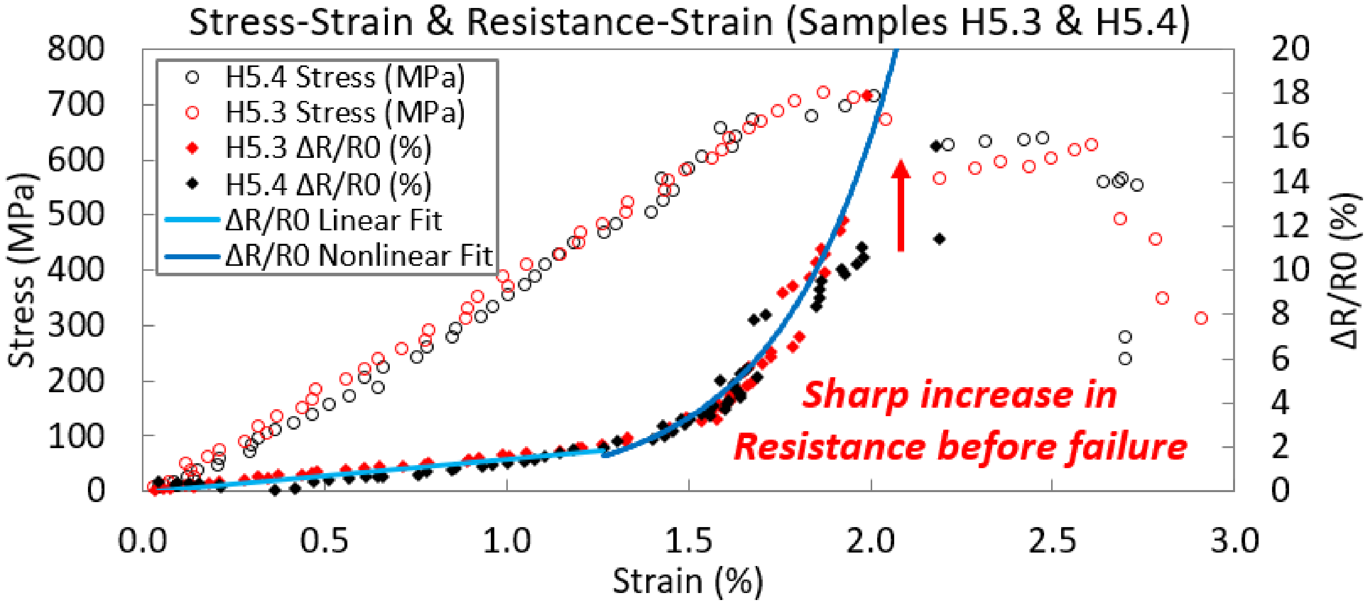
- Use a carbon fiber tow as a strain sensor
- Property of electric conductivity is used in sensing
- Use glass fiber tows for electrical insulation
- Minimum 600% change in resistance at failure





Section View of Hybrid Composite

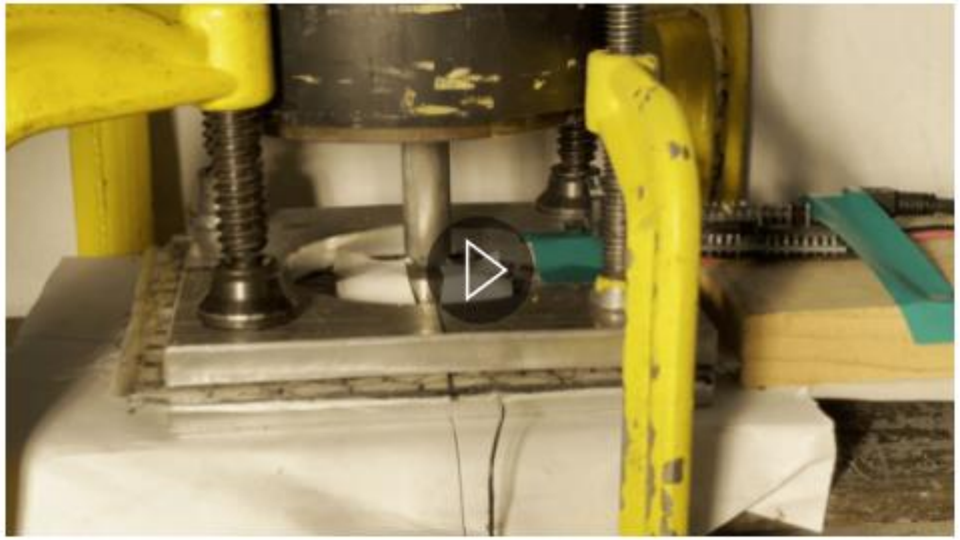
Glass Fiber Tow



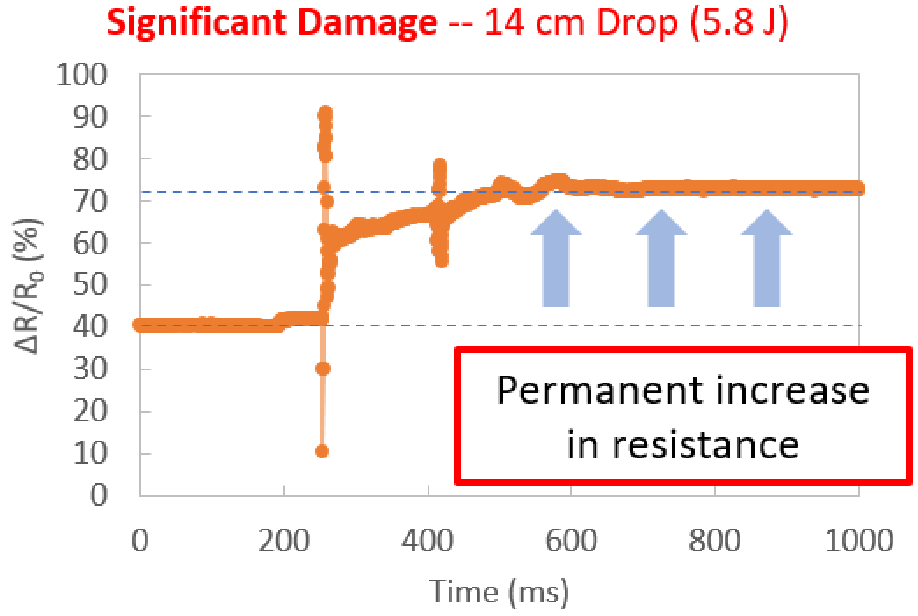
*US. Patent Application No. 17/740,543

Task 1.2.4 –Evaluate and develop required self-health monitoring technologies

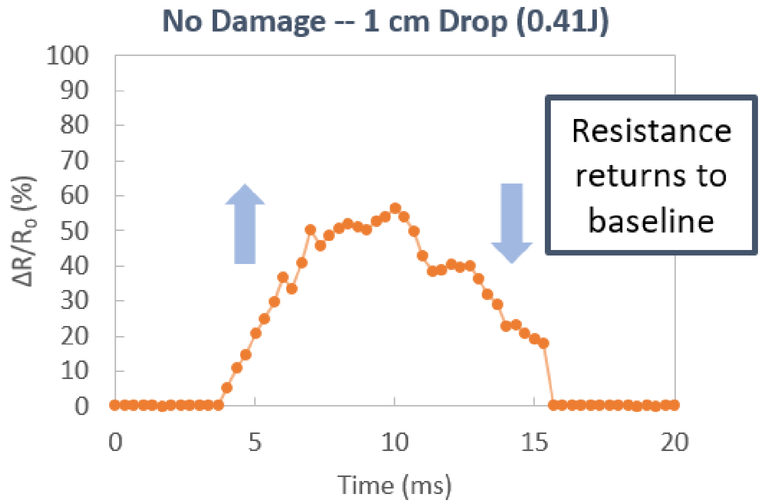
Impact damage sensor



Impact testing machine



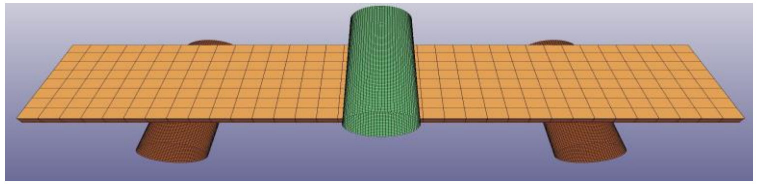
Impact Energy (J)	0.415	0.829	1.244	1.658	1.658	2.073	2.487	2.902	3.316	4.145	4.974	5.804	6.633
$\Delta R/R_0$	0.0%	2.7%	9.3%	10.4%	31.3%	43.0%	24.4%	26.6%	32.8%	37.4%	33.7%	58.0%	68.5%



Sensor successfully detected impact damage from the permanently increased resistance

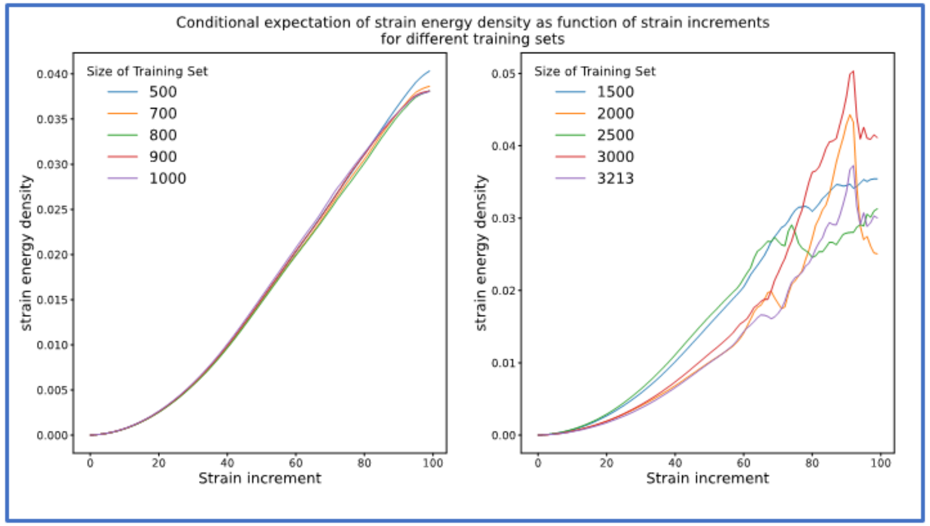
Task 1.2.5 –Evaluate and develop AI/ML technologies for monitoring the manufacturing process

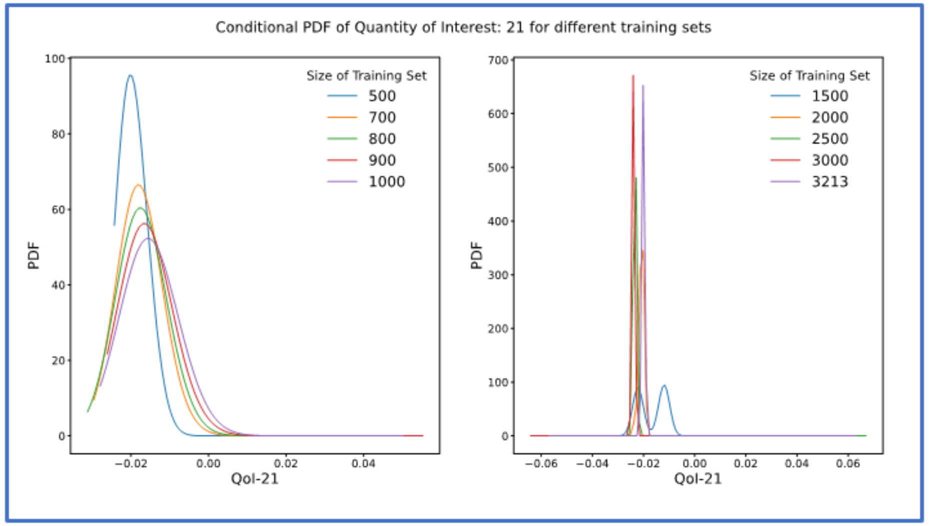
- The AI/ML technology developed in this project is a combination of two techniques, 1) Probability Learning on Manifold; 2) Neural Networks
- Before demonstrating the technology on the process monitoring, the development was demonstrated on a structural problem and the results are provided here.



ML to estimate the joint density function of:

1. Microconstituents (mechanics and Geometry)
2. RVE stress at sequence of strain increments
3. Strain energy density in each phase at sequence of strain increments





Task 1.3 – Initial structural design of battery enclosure

Battery cover

Battery tray

Cross rail

Component	Materials	Process	Features for demonstration
Cover	SMC (intumescent), SMC (Phenolic)	Compression molding	Fire retardant, Variable thickness, AI/ML process
Tray	Coats Lattice	HP-RTM	Complex geometry, moldable preforms, AI/ML strategy
Cross Rails	Lattice preforms	HP-RTM	Complex geometry at the ends

Partners/Collaborators

General Motors

- **Lead – PM**
- Baseline Steel assembly
- Design of composite assembly
- HP-RTM reinforcement
- Structural Design
- Structural testing/ validation

Coats

- Tier 2, technology leader in TFP

Columbia University

- Strong expertise in sensors, energy harvesting technology and data analytics

Teijin

- Key Tier1 supplier
- Process design
- FR material development

ESI

- Virtual prototype software development company, Global technology leader

Michigan State University (IACMI)

- State-of-the-art federally funded facilities for composite manufacturing

University of Southern California

- Expert at AI/ML
- DOE SciDAC institute

Remaining Challenges and Barriers

(Any proposed future work is subject to change based on funding levels)

- Finalize structural design of the composite battery enclosure
- Finalize the process design of the composite assembly
- Finalize AI/ML technology for monitoring the manufacturing process of composite assembly
- Build the manufacturing tools
- Initial manufacturing of components of the assembly

Proposed Future Research

- Develop the material systems for improved performance versus cost, and include multi-functional capability in a cost-effective way
- Develop analytical models to predict the residual life of composites using the developed self-health monitoring system
- Complete the predictive models for both RTM process and structural performance of hybrid composites
- Demonstrate a 3-minute process cycle time
- Develop and demonstrate the AI/ML technology for process monitoring
- Design the battery enclosure with the developed materials and computational tools meeting the critical side pole impact performance

Responses to Previous Year Reviewers' Comments

- Question : The team has an excellent approach to create multifunctional structural battery enclosures. By investigating different routes to make the enclosure multifunctional (i.e., self-health monitoring, fire-retardant, and electromagnetic compatibility), the reviewer believed the probability of success is high for finding a value proposition for these new enclosures. In the next AMR, the reviewer said that it would be good to clarify if all the added functionalities are planned to be integrated into the same enclosure or if different enclosures are being designed to have different functionalities. Also, because this application is highly dependent on cost, a more robust cost analysis of the composite composition would be useful. For example, it was mentioned that E-glass fiber and PX35 Zoltek CF were selected as the fibers, but a lot of different grades of fiberglass and CF are available at different cost points and with different performance properties. A little more discussion on how the team arrived at those specific fibers would be useful in future AMRs. Overall, it was an excellent approach to the battery enclosure problem that will become more prevalent as EV adoption increases.
- Answer: All the added functionalities developed in the project will be integrated and applied on the battery enclosures. We are open to investigating different fibers to make a strong business case. As you can see in the results, we have used T300 fibers, H-glass fibers and even newly arrived Hyosung carbon fibers

Summary

- Hybrid glass and carbon fiber designs were evaluated with different comingling forms and volume fractions to determine an optimum ratio for cost and performance
- Manufacturing models were developed correlating the pressure and the performance within 15% of experimental results.
- Multi-scale models were developed for hybrid glass and carbon fiber composites, and validated the predictions with the experiments (differences within 15%)
- Self-health monitoring technology was developed and demonstrated
- An experimental setup was designed and experimented for the development and validation of the AI/ML process monitoring technology.
- Initial structural design and engineering of the battery enclosures is in progress

Thank You!